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CMS Collaboration ; Canelli, M Florencia ; Kilminster, Benjamin ; Caminada, Lea ; Botta, Cristina ; Aarrestad, Thea K ; Brzhechko, Danyyl ; De Cosa, Annapaola ; Del Burgo, Riccardo ; Donato, Silvio ; Heikkilä, Jaana K ; Leontsinis, Stefanos ; Mikuni, Vinicius M ; Missiroli, Marino ; Neutelings, Izaak ; Rauco, Giorgia ; Robmann, Peter ; Schweiger, Korbinian ; Takahashi, Yuta ; Wertz, Sebastien ; Zucchetta, Alberto ; et al

DOI: <https://doi.org/10.1016/j.physletb.2020.135425>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-196738>

Journal Article

Published Version



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Originally published at:

CMS Collaboration; Canelli, M Florencia; Kilminster, Benjamin; Caminada, Lea; Botta, Cristina; Aarrestad, Thea K; Brzhechko, Danyyl; De Cosa, Annapaola; Del Burgo, Riccardo; Donato, Silvio; Heikkilä, Jaana K; Leontsinis, Stefanos; Mikuni, Vinicius M; Missiroli, Marino; Neutelings, Izaak; Rauco, Giorgia; Robmann, Peter; Schweiger, Korbinian; Takahashi, Yuta; Wertz, Sebastien; Zucchetta, Alberto; et al (2020). A measurement of the Higgs boson mass in the diphoton decay channel. *Physics Letters B*, 805:135425.

DOI: <https://doi.org/10.1016/j.physletb.2020.135425>



A measurement of the Higgs boson mass in the diphoton decay channel

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ARTICLE INFO

Article history:

Received 15 February 2020
Received in revised form 8 April 2020
Accepted 9 April 2020
Available online 15 April 2020
Editor: M. Doser

Keywords:

CMS
Higgs
diphoton

ABSTRACT

A measurement of the mass of the Higgs boson in the diphoton decay channel is presented. This analysis is based on 35.9 fb^{-1} of proton-proton collision data collected during the 2016 LHC running period, with the CMS detector at a centre-of-mass energy of 13 TeV. A refined detector calibration and new analysis techniques have been used to improve the precision of this measurement. The Higgs boson mass is measured to be $m_H = 125.78 \pm 0.26 \text{ GeV}$. This is combined with a measurement of m_H already performed in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel using the same data set, giving $m_H = 125.46 \pm 0.16 \text{ GeV}$. This result, when further combined with an earlier measurement of m_H using data collected in 2011 and 2012 with the CMS detector, gives a value for the Higgs boson mass of $m_H = 125.38 \pm 0.14 \text{ GeV}$. This is currently the most precise measurement of the mass of the Higgs boson.

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1. Introduction

The independent observations of the Higgs boson by the ATLAS and CMS Collaborations [1–3] in proton-proton collisions at the CERN LHC was a key milestone in the understanding of the mechanism of electroweak symmetry breaking. More recently, with the increased amount of data resulting from the higher energy and the higher luminosity accumulated at the LHC between 2015 and 2018 (Run 2), the focus has shifted from observation to precision measurements of its properties. The couplings of the Higgs boson to other elementary particles can be predicted by the standard model of particle physics once its mass is known. This motivates precise measurements of the mass of the Higgs boson (m_H) in all available decay channels.

Although the $H \rightarrow \gamma\gamma$ decay channel has a small ($\approx 0.23\%$) branching fraction, it provides a clean final state topology in which the diphoton invariant mass can be reconstructed with high precision. The measurement of m_H in this decay channel can be combined with measurements in other decay channels to achieve an even higher precision. In this way the ATLAS and CMS Collaborations measured m_H to be $125.09 \pm 0.24 \text{ GeV}$ [4] with the data collected in 2011 and 2012 (Run 1).

In this Letter, we present a new measurement of m_H in the $H \rightarrow \gamma\gamma$ decay channel with the data collected at $\sqrt{s} = 13 \text{ TeV}$ in 2016 corresponding to an integrated luminosity of 35.9 fb^{-1} . The CMS Collaboration has previously reported a measurement of

m_H with the same data set in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel where m_H was measured to be $125.26 \pm 0.21 \text{ GeV}$ [5]. The ATLAS collaboration have also published a measurement of m_H of $124.97 \pm 0.24 \text{ GeV}$ [6], using the combined 2016 and Run 1 data sets. Our measurements of m_H with the 2016 data set, in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels, have been combined with our measurement of m_H with the Run 1 data set. The combined result and the procedure followed for this combination are also described in this Letter.

2. The CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter with a uniform magnetic field of 3.8 T. Inside the magnet volume are silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Gas-ionisation chamber based muon detectors are embedded in the steel flux-return yoke outside the solenoid. The ECAL is a hermetic homogeneous calorimeter made of 61 200 lead tungstate (PbWO_4) crystals mounted in the central barrel part, closed by 7324 crystals in each of the two endcaps. In the region $1.65 < |\eta| < 2.6$ a three-radiation-length-thick preshower detector with two orthogonal layers of silicon strips is placed in front of the endcap crystals. Avalanche photodiodes are used as photodetectors in the barrel and vacuum phototriodes in the endcaps. The barrel part of the ECAL (EB) covers the pseudorapidity range $|\eta| < 1.479$, while the endcap calorimeters cover the range $1.479 < |\eta| < 3.0$. A calorimeter with longitudinal quartz

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fibres complements the coverage provided by the barrel and endcap detectors. The first level of the CMS trigger system [7] uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μ s. The high-level trigger processor farm further decreases the event rate from around 100 kHz to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [8].

3. Analysis strategy

The general strategy followed in this analysis is the same as that adopted in an earlier analysis by the CMS Collaboration of the Higgs boson properties in the diphoton channel [9]. Since that publication, refinements were made to increase the precision of the measurement of m_H through a better understanding of the systematic uncertainties of the measurement, and a more accurate detector calibration was performed. We have also improved the method, first introduced in Ref. [10], to measure and correct for nonlinear discrepancies in the energy scale with transverse momentum (p_T), of electrons from Z boson decay, between data and simulation by increasing the granularity of the correction. In addition, we have developed a method to evaluate the systematic uncertainty of the photon energy scale due to radiation damage of the ECAL crystals, and a simplified event categorisation, described in Section 6, is followed in the analysis.

With the new calibration, the detector response is more stable with time, leading to a reduction of the uncertainties in the corrections to the photon energy due to the material upstream of the ECAL and of the uncertainties associated with variables which describe the electromagnetic shower.

4. Data and simulation

The events used in this analysis were collected in 2016 with an integrated luminosity of 35.9 fb^{-1} . They were selected with a diphoton trigger that had asymmetric p_T thresholds of 30 and 18 GeV. Full details of the trigger selection and the measurement of the trigger efficiency can be found in Ref. [9]. To model the signal and background processes, events are generated with Monte Carlo techniques. The detailed response of the CMS detector is simulated using the GEANT4 package [11].

Signal events are simulated with the MADGRAPH5_AMC@NLO v2.2.2 matrix-element generator [12] at next-to-leading order and interfaced with PYTHIA 8.205 [13] for parton showering and hadronisation. The PYTHIA underlying event tune CUETP8M1 [14] was used. The irreducible prompt diphoton background and the reducible backgrounds of $\gamma + \text{jet}$ and multijet events, where the jets are misidentified as isolated photons, are the dominant backgrounds to the $H \rightarrow \gamma\gamma$ decay process. The diphoton background is modelled with the SHERPA v2.2.1 [15] generator, which includes the Born processes with up to 3 additional jets at leading order (LO) accuracy, as well as the LO box processes. The $\gamma + \text{jets}$ and multijet backgrounds are modelled with PYTHIA at LO. These samples are used for the training of the multivariate discriminants used in this analysis, as well as for the optimisation of the event categorisation. The Drell-Yan samples used to derive the electron and photon energy scale corrections and their systematic uncertainties, are simulated with MADGRAPH [16] and MADGRAPH5_AMC@NLO generators and merged together in order to improve the statistical precision of the scale corrections. Before merging these samples, the compatibility of the m_{ee} lineshapes between the two generators in the categories used to derive the electron and photon energy scale corrections was confirmed.

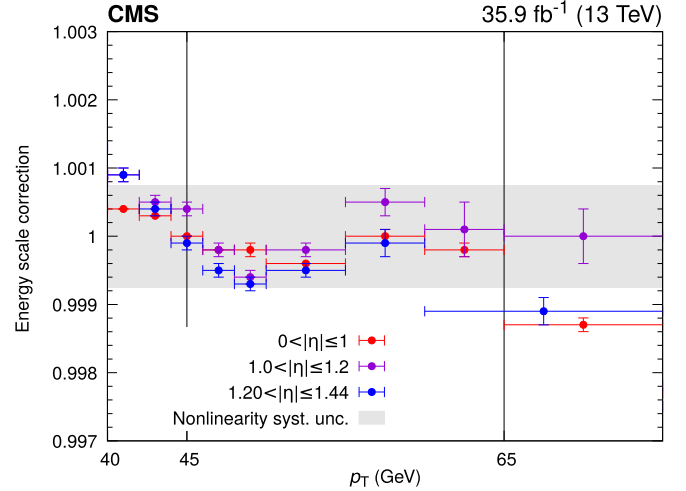


Fig. 1. Energy scale corrections as a function of the p_T of the photon. The horizontal bars in the plot represent the variable bin width. The systematic uncertainty associated with this correction is approximately the maximum deviation observed in the p_T range between 45 and 65 GeV for electrons in the EB region.

The simulation includes multiple proton-proton interactions taking place within a bunch crossing, known as ‘pileup’. Pileup can occur not only in the same bunch crossing (in-time pileup), but also in the crossing of previous and subsequent bunches (out-of-time pileup), both of which are accounted for by the simulation. The simulated events are scaled to reproduce the distribution of the number of pileup interactions in data.

5. Photon reconstruction and identification

Photon candidates are reconstructed as energy deposits in a collection of crystals in the ECAL. A cluster is formed by first identifying a ‘seed’ crystal with an energy above a given threshold, then the cluster is built by finding the crystals that share an edge with the seed crystal and have an energy above another, lower threshold. This second threshold is set to be approximately 80 MeV in the barrel and ranging from 80 to 300 MeV in the endcaps, depending on $|\eta|$. These clusters, once formed, are combined to form a ‘supercluster’, aiming to fully contain the shower of the photon. This procedure accounts for variations in geometry as a function of $|\eta|$, and optimises the robustness of the energy resolution against pileup.

5.1. Photon energy calibration

A critical component of the measurement of m_H is the energy calibration of the response of the ECAL to photons. The energy of a photon is calculated by summing the calibrated and corrected energy [17] of all crystals in the associated supercluster, and the energy deposited in the preshower in the region $1.65 < |\eta| < 2.6$ covered by this detector. For each supercluster, a shower shape variable R_9 is defined, which is used to select photons undergoing a conversion in the material between the interaction point and the front face of the ECAL. The variable R_9 is defined for a candidate electromagnetic cluster as the ratio of the sum of energy deposited in a 3×3 crystal array, centred on the crystal with the highest energy, to the sum of the energy in the supercluster. The energy deposition of photons that convert before reaching the calorimeter tends to have wider transverse profiles and thus lower values of R_9 than those of unconverted photons. To further optimise the energy resolution, the energy is corrected for the lack of complete containment of the electromagnetic showers in the clustered crystals, the energy lost by photons that convert upstream

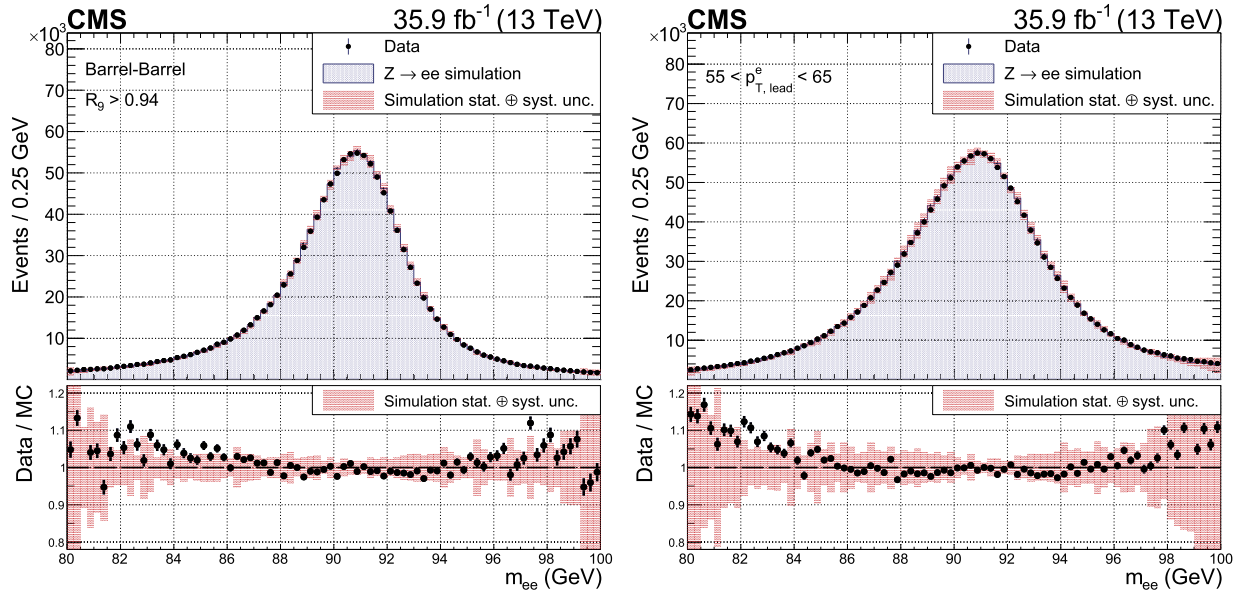


Fig. 2. Comparison of the distributions of the invariant mass of the dielectrons in data and simulation in $Z \rightarrow ee$ events after application of energy corrections in two representative categories. Left: Both electrons are in the EB and satisfy $R_9 > 0.94$. Right: the leading electron has a transverse momentum between 55 and 65 GeV, without a requirement on the second electron. The systematic uncertainty in the error band in the plots include only the uncertainties on the derived energy scale corrections.

of the calorimeter, and the effects of pileup. These corrections are derived using a multivariate regression technique, trained on simulated events, which simultaneously estimates the energy of the photon and its median uncertainty. The inputs to this regression are shower shape variables, the preshower information, and observables sensitive to pileup [18].

After applying these corrections to the photon energy, some residual differences remain between the data and simulation in both the photon energy scale and the resolution. A multistep procedure is used to correct these differences, using $Z \rightarrow ee$ decays in which the electron showers are reconstructed as photons, so that the simulation accurately reproduces the data. In the first step of this process, any residual long-term drifts in the energy scale in data are corrected for, in approximately 18-hour intervals corresponding to one LHC fill. In the second step, corrections to both the energy resolution in the simulation, and the scale correction needed for the data are derived simultaneously in bins of $|\eta|$ and R_9 for electrons. The energy resolution obtained in simulation is matched to the data by adding a Gaussian smearing term, determined by adjusting the agreement in the $Z \rightarrow ee$ invariant mass distributions. In the third and final step the energy scale corrections are derived in bins of $|\eta|$ and p_T to account for any nonlinear response of the crystals with energy. The corrections obtained from this step are shown in Fig. 1 for electrons as a function of p_T in the three bins of $|\eta|$ in EB. This additional step in the scale correction improves the precision of the measurement of m_H , since the energy spectrum of the electrons from Z boson decay ($\langle p_T \rangle \approx 45$ GeV) used to derive the scale corrections, is different from the energy spectrum of photons from Higgs boson decay ($\langle p_T \rangle \approx 60$ GeV).

We note that in the second step the number of bins in R_9 for the scale corrections has been increased by a factor of five over the previous analysis [9], resulting in an improvement in the precision with which the energy scale is determined. Also, in order to provide a consistency test of the derivation procedure, the correction factors that are obtained in the second and third steps are applied a second time to the data and a new set of factors is extracted in the same electron categories. Any deviation from unity is an indication of the nonclosure of the derivation procedure and is applied as a systematic uncertainty on scale corrections.

The agreement between data and simulation in the dielectron invariant mass, after applying these energy scale corrections and the additional smearings, is shown in Fig. 2 for dielectron events in the EB with R_9 greater than 0.94, and for dielectron events with a leading transverse momentum between 55 and 65 GeV, without a requirement on the second electron. The former demonstrates the performance of the energy corrections on photons with the highest event count, optimal resolution, and the highest sensitivity to the Higgs boson mass. The latter demonstrates that the energy corrections are effective in a kinematic region where the p_T of the electron has been chosen to be the typical p_T of a photon from a Higgs boson decay. In both cases data and simulation are in good agreement in the core of the distributions.

5.2. Photon preselection and identification

The photons considered in the subsequent steps of this analysis are required to satisfy certain preselection criteria that are similar to, but more stringent than, those imposed by the trigger requirements. A detailed description of these preselection criteria, as well as the methods employed to evaluate their efficiencies, can be found in Ref. [9]. A dedicated boosted decision tree (BDT) is used to classify prompt photons from other photon candidates that arise out of misidentified jet fragments, but which satisfy the preselection criteria. The full details of the input features of this photon identification BDT is also described in Ref. [9]. The score of this BDT is used later in the event categorisation, discussed in the next section.

5.3. Vertex selection

The identification of the diphoton vertex position along the beam axis has a direct impact on the diphoton mass resolution, since if the vertex position is known to better than about 1 cm, then the invariant mass resolution is dominated by the photon energy resolution. The distribution of the position of the interaction vertices along the beam axis has an RMS spread of about 3.4 cm, and, in typical pileup conditions in 2016, there were on average around 23 interactions in each bunch crossing. The choice of the diphoton vertex is made following the same procedure in

Ref. [9]: a BDT, whose inputs are observables related to tracks recoiling against the diphoton system, is used to identify the most likely vertex. A second BDT is used to determine the probability of correctly choosing that vertex. The score of the second BDT is used later in the event categorisation, discussed below. The algorithm is validated using $Z \rightarrow \mu^+\mu^-$ events with the muon tracks removed so as to mimic diphoton pair production. The efficiency of assigning the event to a vertex within 1 cm of the true vertex in the simulated $H \rightarrow \gamma\gamma$ events is found to be approximately 81%.

6. Event classification

The event selection procedure is similar to that in Ref. [9]. The p_T of the two leading photons ($p_T^{\gamma 1}, p_T^{\gamma 2}$) are required to satisfy $p_T^{\gamma 1} > m_{\gamma\gamma}/3$ and $p_T^{\gamma 2} > m_{\gamma\gamma}/4$, where $m_{\gamma\gamma}$ is the diphoton mass, and the photon p_T requirement is applied after the vertex assignment. Additionally $m_{\gamma\gamma}$ is required to be between 100 and 180 GeV. The use of p_T thresholds scaled with the diphoton invariant mass is to prevent a distortion of the lower end of the invariant mass spectrum. The superclusters of both photons are required to have $|\eta| < 2.5$ and to be outside of the barrel-endcap transition region, $1.44 < |\eta| \leq 1.57$.

To improve the sensitivity of the analysis, events are classified according to their production mechanism, mass resolution, and their predicted signal-to-background ratio. A dedicated classifier, referred to as the diphoton BDT, is used to discriminate between signal and background events. This BDT assigns a high score to events with photons exhibiting signal-like kinematics, a good mass resolution, and a high score from the photon identification BDT. The per-event probability estimate of assigning the correct primary vertex to the diphoton system is used as one of the input features of this diphoton BDT. The other input features are described in Ref. [9].

Nearly 95% of Higgs boson events come from two production modes. These are gluon-gluon fusion (ggH) and vector boson fusion (VBF), where there are two jets in the final state separated by a large rapidity gap. A multivariate discriminant is trained to discriminate VBF events from ggH+ jets events, using the kinematics of the characteristic VBF dijet system as inputs. This discriminant is then given as an input to an additional multivariate classifier (VBF combined BDT) along with the score from the diphoton BDT, and the ratio $p_T^{\gamma\gamma}/m_{\gamma\gamma}$. The VBF events are subdivided into three categories based on the VBF combined BDT score. The remaining events are mostly ggH events and are designated as ‘untagged’. These events are further subdivided into four categories based on their diphoton BDT score.

Adding other possible analysis categories, where for example, the Higgs boson is produced in association with a vector boson, or with a pair of top quarks, adds only a small increment to the precision of the mass measurement at the cost of a significant increase in the analysis complexity. Thus, unlike in the earlier analysis [9], these production modes are not considered as separate categories in this analysis.

7. Signal and background models

In order to extract m_H , signal and background models are constructed to fit the diphoton mass distributions observed in the data. The signal models are derived using simulated Higgs boson events, while the background models used in the fits of the $m_{\gamma\gamma}$ spectra are derived directly from data.

7.1. Signal model

The resolution of m_H in the diphoton decay channel depends on the production mechanism and the analysis category. Hence the

signal shapes used to model the diphoton invariant mass distributions are derived for every analysis category and with a nominal value for m_H , using simulated events from the different production modes. The simulation accounts for the trigger, reconstruction, and identification efficiencies, which are measured with data-driven techniques. A weight is applied to the simulated events so that the distribution of the number of interactions per bunch crossing and the location of the primary vertex are matched to the distributions observed in data. A detailed description of each of these steps can be found in Ref. [9].

Since the distribution of $m_{\gamma\gamma}$ depends on the correct assignment of the vertex associated with the diphoton candidate, signal models were constructed with correct and wrong vertex assignment scenarios separately. For each process, analysis category, and vertex scenario, the $m_{\gamma\gamma}$ distributions were fit with a sum of, at most, four Gaussian functions.

For each process, analysis category, and vertex scenario, a simultaneous fit of the signal samples at mass values ranging from 120 to 130 GeV is performed to obtain the variations of the parameters of the Gaussian functions, described by polynomials in m_H , used in the signal model fit.

The final fit function for each category is obtained by summing the functions for all production modes normalised to the expected signal yields in that category. Fig. 3 shows the signal model corresponding to $m_H = 125$ GeV for the best resolution category, which is the untagged events with the highest signal-to-background ratio and the highest diphoton BDT score, ‘Untagged 0’. Also shown in the same figure is the signal model for the sum of all categories, with each category weighted by the corresponding $S/(S+B)$ ratio, where S is the number of signal events, and B is the number of background events in a window around the m_H peak. In the figure the effective width (σ_{eff}), defined as half of the smallest interval that contains 68.3% of the invariant mass distribution, is given, as is the full width at half maximum (FWHM).

7.2. Background model

The model used to describe the background for each of the analysis categories is obtained from data using the discrete profiling method [19]. In this method, a large set of candidate function families is considered, including exponential functions, Bernstein polynomials, Laurent series, and power law functions. These are fit to the $m_{\gamma\gamma}$ distribution in the mass range of 100 to 180 GeV. For each family of functions, a Fisher test [20] is performed to determine the maximum order to be used in the fit, while the minimum order is determined by placing a requirement on the goodness of the fit to the data. The choice of the background function is treated as a discrete nuisance parameter in the fit to account for the uncertainty associated with the arbitrary choice of the function.

8. Systematic uncertainties

The systematic uncertainties are treated differently depending on their effect on the diphoton invariant mass distributions in the different signal categories. The systematic uncertainties in the photon energy scale and resolution modify the shape of the diphoton mass distribution in the signal model. Other systematic uncertainties, while not affecting the signal shape, affect the event yield. The sources of uncertainty included in previous CMS $H \rightarrow \gamma\gamma$ analyses are described in Ref. [9]. A more precise determination of the systematic uncertainties in the photon energy scale and resolution has been developed for the present analysis and is described here.

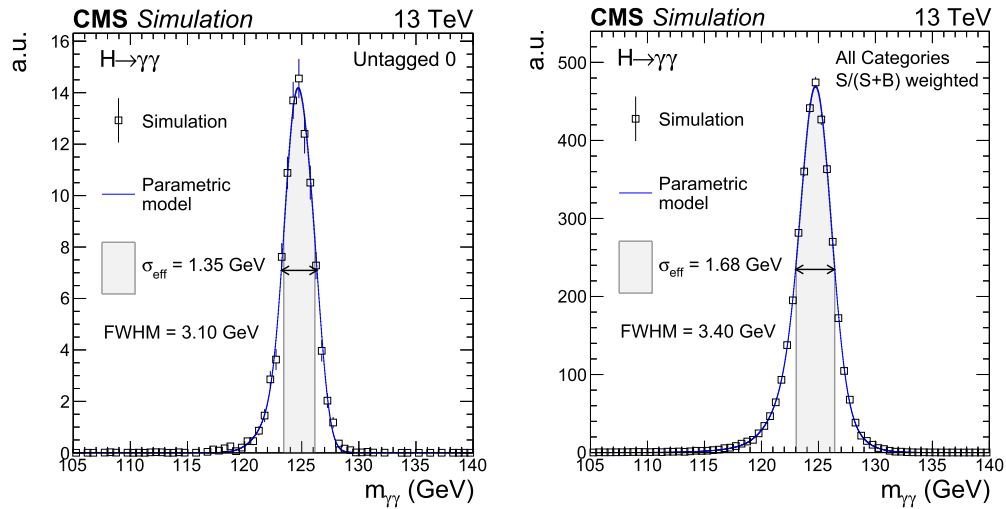


Fig. 3. The signal shape models for the highest resolution analysis category (left), and the sum of all categories combined together after scaling each of them by the corresponding $S/(S+B)$ ratio (right) for a simulated $H \rightarrow \gamma\gamma$ signal sample with $m_H = 125$ GeV. The open squares represent weighted simulated events and the blue line represents the corresponding model. Also shown are the σ_{eff} value (half the width of the narrowest interval containing 68.3% of the invariant mass distribution) and the full width at half maximum (FWHM).

8.1. Uncertainties in the photon energy scale estimated with electrons

The following sources of systematic uncertainties in the photon energy scale were first estimated using electrons and propagated to the photons.

- **Electron energy scale and resolution:** The uncertainty in the electron energy scale and resolution corrections are derived using $Z \rightarrow ee$ events by varying the distribution of R_9 , the electron selections used in the derivation of the corrections, and the transverse energy thresholds on the electron pairs used in the derivation of the corrections. This uncertainty is 0.05–0.1% for electrons in the EB, and 0.1–0.3% for electrons in the ECAL endcaps.
- **Residual p_T dependence of the energy scale correction:** Since the corrections for the residual differences between data and simulation were estimated with $Z \rightarrow ee$ events ($\langle p_T \rangle \approx 45$ GeV), applying them to photons with $\langle p_T \rangle \approx 60$ GeV introduces an additional systematic error. The degree of nonclosure of the p_T -dependent electron energy scale corrections, as described in Section 5.1, is used as the estimate of this source of uncertainty, and is indicated by the band labelled as nonlinearity in Fig. 1. For electrons having $p_T < 80$ GeV, corresponding to all analysis categories except the Untagged 0 category, this uncertainty is 0.075%. For electrons having p_T greater than 80 GeV, corresponding to the Untagged 0 category, the uncertainty is 0.15%. This uncertainty is applied conservatively on the global energy scale and is correlated among all photon candidates.

8.2. Uncertainties due to differences between electrons and photons

Additional systematic uncertainties due to the differences between the response of ECAL to electrons and photons were studied and assigned as follows:

- **Modelling of the material budget:** The uncertainty in the material budget between the interaction point and the ECAL, which affects electron and photon showers differently, was evaluated as described in Ref. [9], and is at most 0.24% of the photon energy scale.
- **Nonuniformity of the light collection:** The shower maximum for photons is deeper than that of electrons by approximately one radiation length, which is 0.89 cm in lead tungstate. Hence the

differences in the light collection efficiency along the length of the ECAL crystals will introduce a difference in the ECAL response to electrons and photons. To account for this, an additional systematic uncertainty is assigned to the photon energy scale. Due to the increase in the radiation damage to the ECAL crystals in Run 2 compared to Run 1, the impact of the nonuniformity in light collection efficiency has become more important. Therefore, a special effort has been made to study this effect and to better estimate the associated systematic uncertainty in the photon energy scale. This is estimated using a light collection efficiency model derived from a detailed optical simulation [21] and validated with measurements made with irradiated crystals [22]. This model takes into account the nonuniformity of the collection of scintillation light due to radiation damage and the crystal geometry. This uncertainty has been evaluated as a function of p_T , supercluster $|\eta_{SC}|$, and R_9 using the radiation damage conditions experienced in the 2016 data taking period. The results are summarised in Fig. 4. The effect is less than 0.16% in the barrel and less than 0.45% in the endcap, and affects photons with $R_9 > 0.96$ the most. The uncertainty is assumed to be correlated among the different $|\eta|$ and R_9 bins but uncorrelated between the barrel and endcap regions due to the difference in the degree of radiation damage and crystal size.

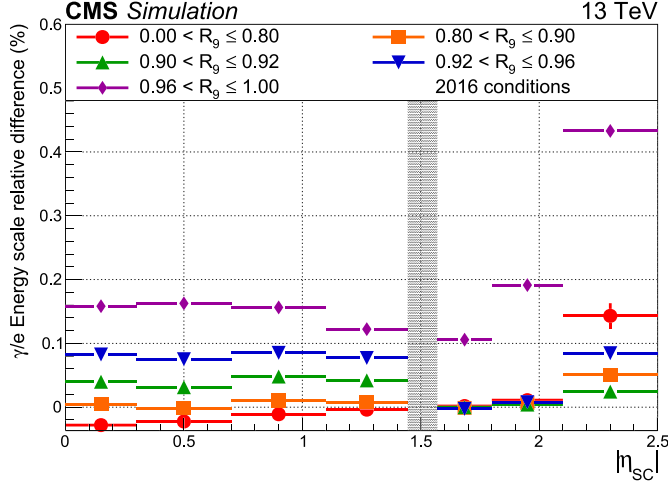
- **Mis-modelling of the input variables to the energy correction:** The uncertainty in the photon energy scale due to imperfect modelling of the shower shape in the simulation is found to be negligible (less than 10 MeV) as a result of the good agreement between data and simulation in the different input variables used in the photon energy regression correction.

8.3. Impact of the sources of uncertainty

The contribution of each source of the photon energy scale systematic uncertainty to the total uncertainty in the m_H measurement was evaluated by performing a likelihood scan removing all but that source and subtracting the statistical uncertainty in quadrature. The results are summarised in Table 1. The leading sources of systematic uncertainty affecting m_H are the residual p_T dependence of the photon energy scale, nonuniformity of light collection, and the electron energy scale and resolution correction.

Table 1The observed impact of the different uncertainties on the measurement of m_H .

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

**Fig. 4.** The systematic uncertainty due to the difference between the electron and photon energy scales from the radiation damage induced nonuniformity of light collection in ECAL crystals in different supercluster $|\eta_{sc}|$ and R_9 categories. The method used to evaluate this uncertainty is described in Section 8.2.

The impact of all other sources of systematic uncertainty were found to be negligible.

9. Results

To extract the measured value of m_H and its uncertainty, a binned maximum likelihood fit is performed simultaneously to the $m_{\gamma\gamma}$ distributions of the seven analysis categories described in Sec. 6, in the range $100 < m_{\gamma\gamma} < 180$ GeV. We use binned fits to reduce computation time and a bin size of 0.125 GeV, which is small compared to the diphoton mass resolution. The data and the signal-plus-background model fit for the sum of all analysis categories is shown in Fig. 5.

The expected number of signal events for each category is summarised in Fig. 6, where the contribution of each production mode to each analysis category is shown. The σ_{eff} and σ_{HM} are also listed; the latter is the FWHM, divided by 2.35.

In the likelihood scan of m_H , other parameters of the signal and background models are allowed to vary. Systematic uncertainties are included in the form of nuisance parameters, and the results are obtained using an asymptotic approach [23] with a test statistic based on the profile likelihood ratio [24]. In the fit to extract m_H , two independent signal strengths for the $(\text{ggH}, \text{t}\bar{\text{t}}\text{H}) \rightarrow \gamma\gamma$ and $(\text{VBF}, \text{VH}) \rightarrow \gamma\gamma$ processes are free to vary. The best-fit mass of m_H is observed to be $m_H = 125.78 \pm 0.18(\text{stat}) \pm 0.18(\text{syst})$ GeV, while it was expected to have a statistical uncertainty of ± 0.21 GeV and a systematic uncertainty of ± 0.18 GeV. The signal strengths obtained were found to be compatible with the same from previous analysis in the diphoton decay channel [9]. The expected uncertainties in the measurement were obtained by generating an Asimov data set [24] from the expected signal from the standard model plus best-fit background model. The difference between the measured

values of m_H in the $H \rightarrow \gamma\gamma$ channel in the two LHC run periods, Run 1 [10] and 2016, is $\Delta m_H = 1.12 \pm 0.43$ GeV. The compatibility of these two results is at the level of 2.6 standard deviations. A detailed set of cross-checks was performed to ensure that this shift is statistical.

9.1. Combination with the $H \rightarrow ZZ \rightarrow 4\ell$ mass measurement in the 2016 and Run 1 data sets

The results of this mass measurement were combined with a measurement of the same quantity in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with the 2016 data set reported by CMS in Ref. [5] using the same data set with a preliminary set of detector conditions.

In the combination a possible correlation may exist between electron and photon energy scales. In the $H \rightarrow \gamma\gamma$ decay channel, the largest contribution to the uncertainty on the photon energy scale is due to the difference in the calorimeter response to electrons and photons, which is only applied to the $H \rightarrow \gamma\gamma$ decay channel. Other differences between the two decay channels in the derivation of the energy scale corrections are the much finer binning in R_9 and their p_T -dependence in the $H \rightarrow \gamma\gamma$ decay channel. Additionally the average energy of the electrons in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel is much lower than the most probable photon energy in the $H \rightarrow \gamma\gamma$ decay channel. Thus we treat the uncertainties, residual to the electron-photon difference, in the electron and photon energy scales to be uncorrelated between the two channels.

The combined value of m_H measured from the 2016 data set is observed to be $m_H = 125.46 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$ GeV with an expected statistical uncertainty of ± 0.16 GeV and an expected systematic uncertainty of ± 0.10 GeV. Three independent signal strengths for the $(\text{ggH}, \text{t}\bar{\text{t}}\text{H}) \rightarrow \gamma\gamma$, $(\text{VBF}, \text{VH}) \rightarrow \gamma\gamma$ and $\text{pp} \rightarrow H \rightarrow ZZ \rightarrow 4\ell$ processes are free to vary in the fit to extract m_H , so that we are not completely dependent on the standard model for the production and decay ratios. This result is in good agreement with the ATLAS+CMS Run 1 measurement [4], $m_H = 125.09 \pm 0.24$ GeV. A scan of the value of twice the negative logarithm of the likelihood ($-2\Delta\ln L$) as a function of m_H for the two individual decay channels, as well as their combination is shown in Fig. 7.

The same procedure was used to combine this result from the 2016 data set with the same measurement ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$) obtained from the Run 1 data [25]. The result of combining the measurements from both data taking periods is $m_H = 125.38 \pm 0.11(\text{stat}) \pm 0.08(\text{syst})$ GeV with an expected statistical uncertainty of ± 0.13 GeV and an expected systematic uncertainty of ± 0.08 GeV. Fig. 8 shows the likelihood scans of the combined Higgs boson mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels with the Run 1 and 2016 data sets individually and the same combining the two data sets. A summary of the individual and combined measurements with the Run 1 and 2016 data sets is shown in Fig. 9.

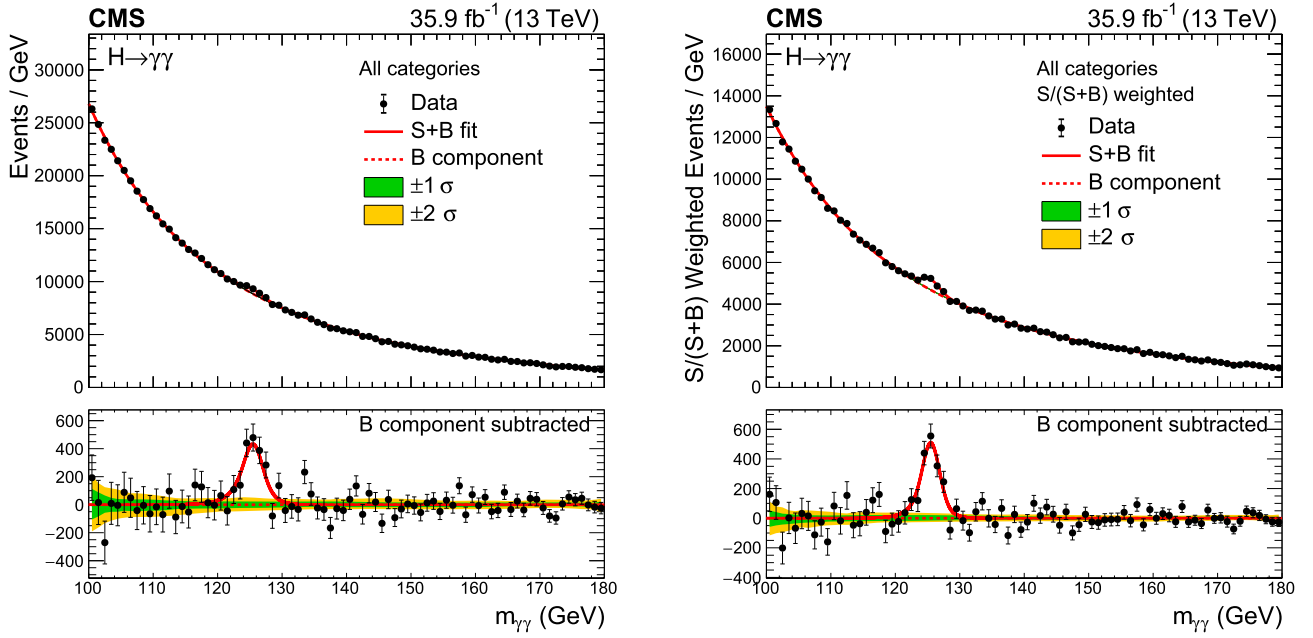


Fig. 5. Data and signal-plus-background model fit for all categories summed (left) and where the categories are summed weighted by their corresponding sensitivities, given by $S/(S+B)$ (right). The one (green) and two (yellow) standard deviation bands include the uncertainties in the background component of the fit. The lower panel in each plot shows the residuals after the background subtraction.

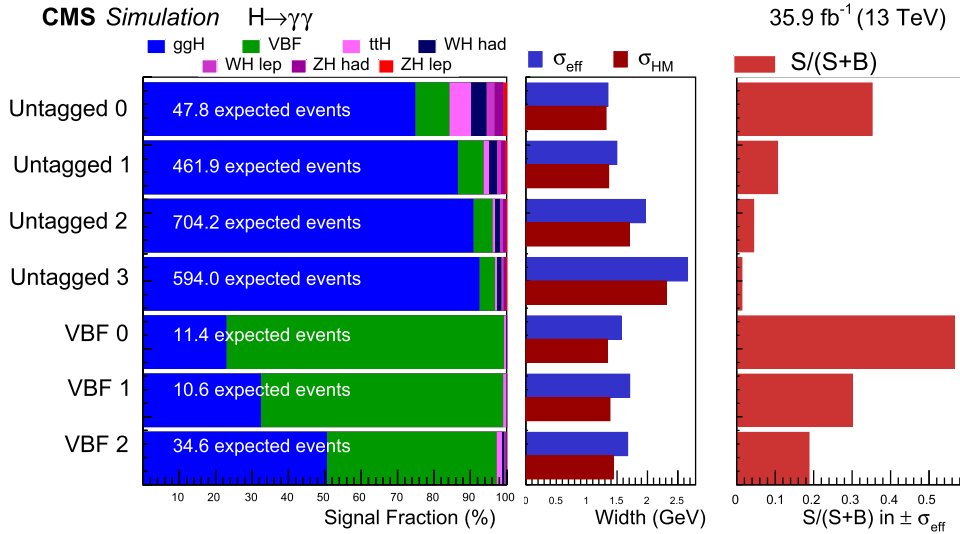


Fig. 6. The expected number of signal events per category and the percentage breakdown per production mode. The σ_{eff} value (half the width of the narrowest interval containing 68.3% of the invariant mass distribution) is also shown as an estimate of the $m_{\gamma\gamma}$ resolution in that category and compared directly to the σ_{HM} . The ratio of the number of signal events (S) to the number of signal plus background events ($S+B$) is shown on the right-hand panel.

10. Summary

In this Letter we describe a measurement of the Higgs boson mass in the diphoton decay channel with 35.9 fb^{-1} of data collected in 2016 at $\sqrt{s} = 13 \text{ TeV}$ at the LHC. New analysis techniques have been introduced to improve the precision of the measurement and we have used a refined detector calibration. The technique that is new with respect to the previous analysis in the diphoton decay channel [9] is the introduction of residual energy corrections in much finer bins of η , p_T and the shower shape variable R_9 of the electrons from $Z \rightarrow ee$ decays, in which the electron showers are reconstructed as photons. We have also employed a new method to estimate the systematic uncertainty due to changes in the transparency of the crystals in the electromagnetic calorimeter with radiation damage. The measured value of

the Higgs boson mass in the diphoton decay channel is found to be $m_H = 125.78 \pm 0.26 \text{ GeV}$. This measurement has been combined with a recent measurement by CMS of the same quantity in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel [5] to obtain a value of $m_H = 125.46 \pm 0.16 \text{ GeV}$. Furthermore, when the Run 2 result with the 2016 data set is combined with the same measurement performed in Run 1 at 7 and 8 TeV the value of the Higgs boson mass is found to be $m_H = 125.38 \pm 0.14 \text{ GeV}$. This is currently the most precise measurement of the mass of the Higgs boson.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS in-

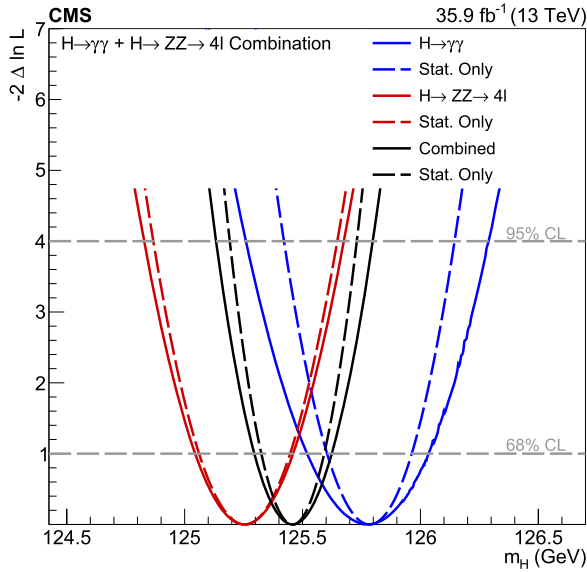


Fig. 7. The likelihood scan of the measured Higgs boson mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels individually and for the combination with the 2016 data set. The solid lines are for the full likelihood scan including all systematic uncertainties, while the dashed lines denote the same with the statistical uncertainty only.

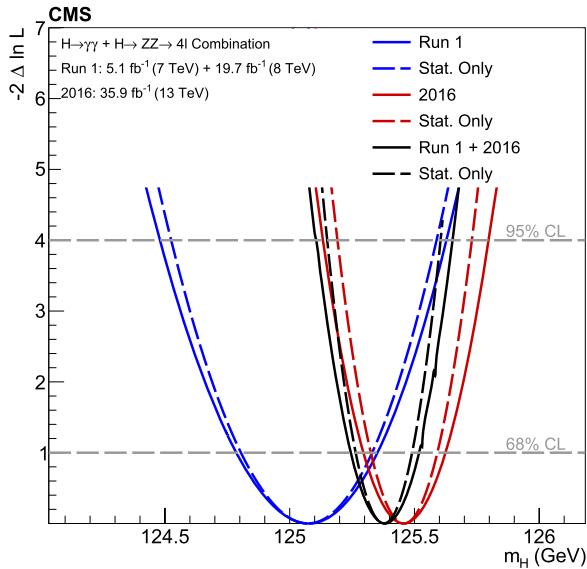


Fig. 8. The likelihood scan of the combined Higgs boson mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels with the Run 1 and 2016 data sets and the same combining the two data sets. The solid lines are for the full likelihood scan including all systematic uncertainties, while the dashed lines denote the same with the statistical uncertainty only.

stitutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3

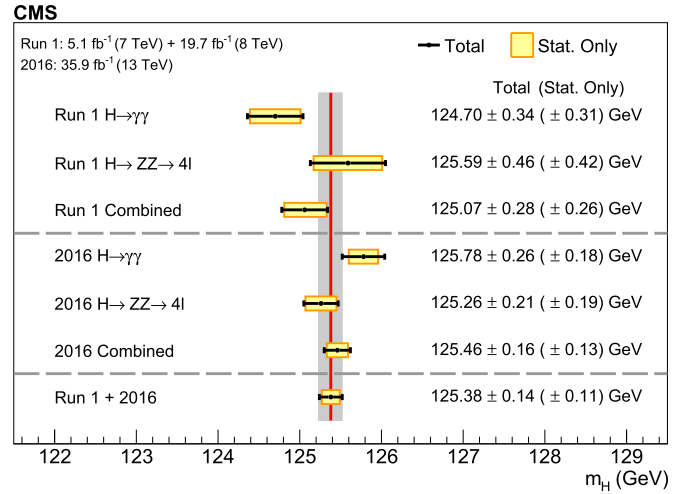


Fig. 9. A summary of the measured Higgs boson mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels, and for the combination of the two is presented here. The statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (grey) shaded column indicate the central value and the total uncertainty of the Run 1 + 2016 combined measurement, respectively.

(France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NK-FIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy - EXC 2121 "Quantum Universe" - 390833306; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 14.W03.31.0026 (Russia); the Programa Estatal de Fomento de la

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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- 40 Also at Imperial College, London, United Kingdom.
- 41 Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- 42 Also at California Institute of Technology, Pasadena, USA.
- 43 Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- 44 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- 45 Also at Università degli Studi di Siena, Siena, Italy.
- 46 Also at INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy, Pavia, Italy.
- 47 Also at National and Kapodistrian University of Athens, Athens, Greece.
- 48 Also at Universität Zürich, Zurich, Switzerland.
- 49 Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria.
- 50 Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey.
- 51 Also at Şırnak University, Şırnak, Turkey.
- 52 Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China.
- 53 Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- 54 Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey.
- 55 Also at Istanbul Aydın University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- 56 Also at Mersin University, Mersin, Turkey.
- 57 Also at Piri Reis University, Istanbul, Turkey.
- 58 Also at Gaziosmanpaşa University, Tokat, Turkey.
- 59 Also at Ozyegin University, Istanbul, Turkey.
- 60 Also at Izmir Institute of Technology, Izmir, Turkey.
- 61 Also at Bozok Üniversitesi Rektörlüğü, Yozgat, Turkey.
- 62 Also at Marmara University, Istanbul, Turkey.
- 63 Also at Kafkas University, Kars, Turkey.
- 64 Also at Istanbul Bilgi University, Istanbul, Turkey.
- 65 Also at Hacettepe University, Ankara, Turkey.
- 66 Also at Adiyaman University, Adiyaman, Turkey.
- 67 Also at Vrije Universiteit Brussel, Brussel, Belgium.
- 68 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 69 Also at IPPP Durham University, Durham, United Kingdom.
- 70 Also at Monash University, Faculty of Science, Clayton, Australia.
- 71 Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- 72 Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- 73 Also at Bingöl University, Bingöl, Turkey.
- 74 Also at Georgian Technical University, Tbilisi, Georgia.
- 75 Also at Sinop University, Sinop, Turkey.
- 76 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- 77 Also at Nanjing Normal University Department of Physics, Nanjing, China.
- 78 Also at Texas A&M University at Qatar, Doha, Qatar.
- 79 Also at Kyungpook National University, Daegu, Korea, Daegu, Republic of Korea.